

# Hydrodynamics in small systems

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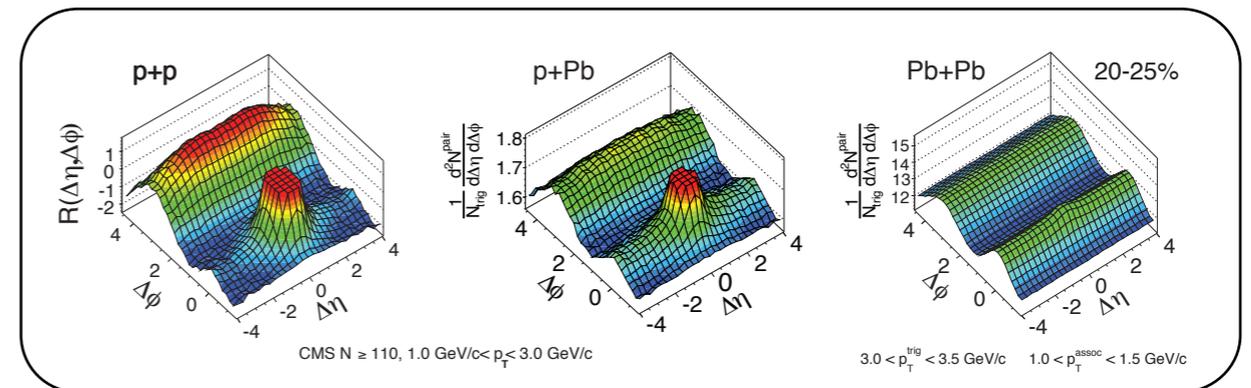
**BROOKHAVEN**  
NATIONAL LABORATORY

# Introduction: Small systems p+p, p+A, d+A, $^3\text{He}+A$

- High multiplicity p+p and p+Pb collisions at LHC show similar features as Pb+Pb collisions (ridge,  $v_n$ )

- d+Au at RHIC also seems to show similar features

- Interpretation not yet clear:



- Initial correlations? Theory on this is developing: new insights

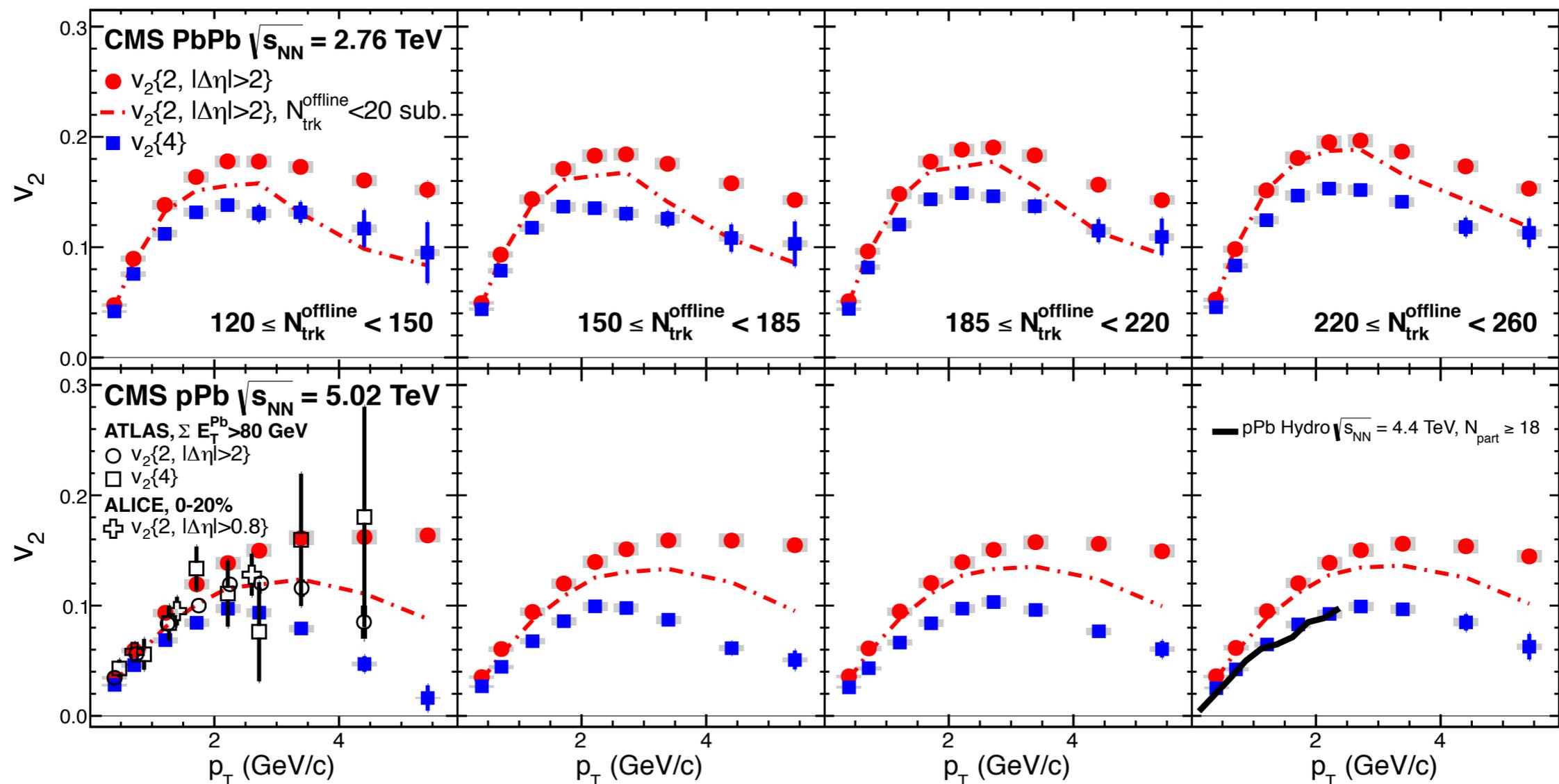
- Initial geometry + collective effects? Fluid dynamics?

- **How well can fluid dynamics do? What are calculations sensitive to? When does hydro break down?**

# Why fluid dynamics?

- A motivation for using hydrodynamics in small systems is its success in larger systems and the similarity of experimental data in p+A and A+A collisions

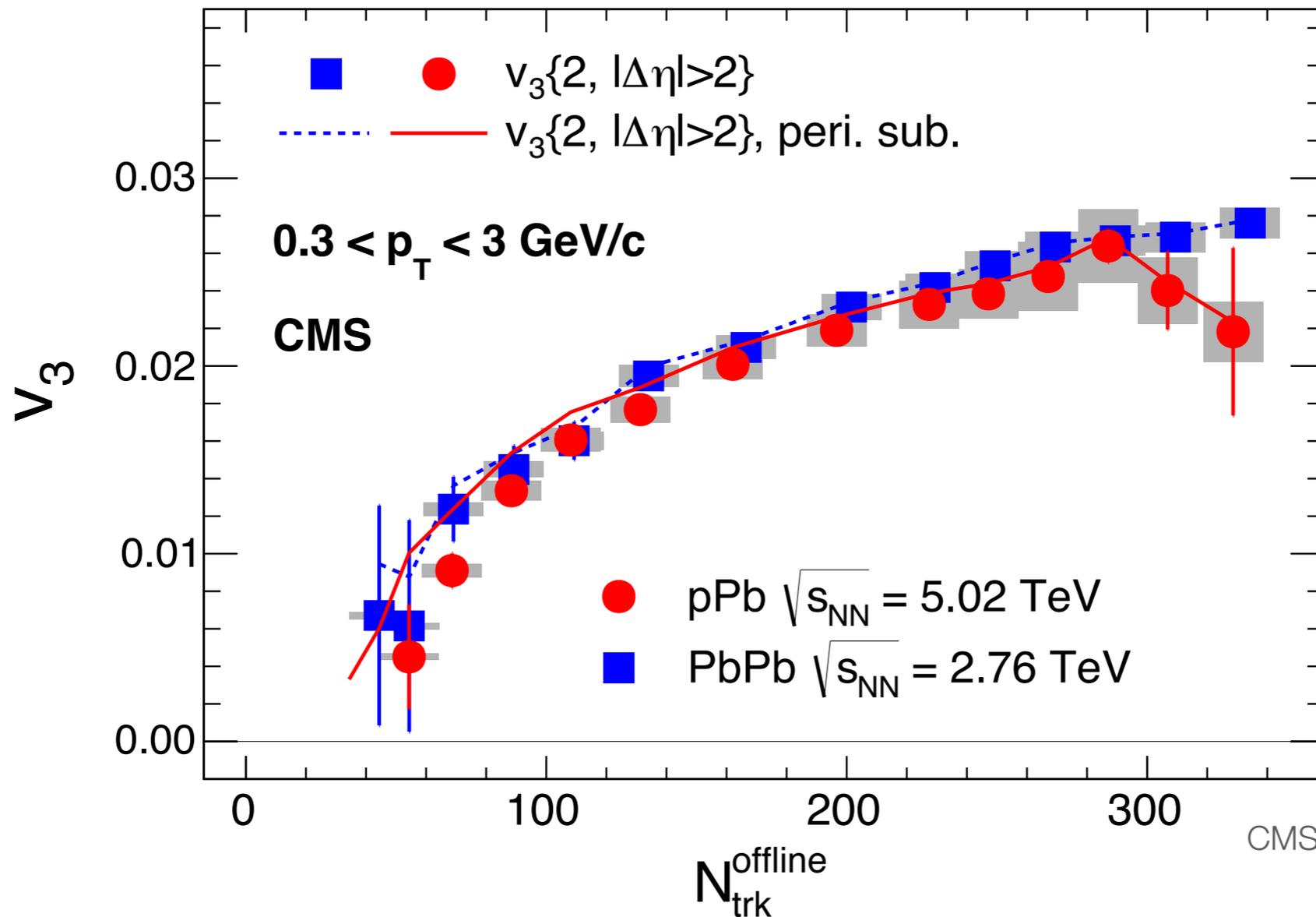
CMS, Phys. Lett. B 724 (2013) 213



Although, the initial states are likely to look quite different

# Why fluid dynamics?

- Similarity of experimental data in p+A and A+A collisions



CMS, Phys. Lett. B 724 (2013) 213

see also

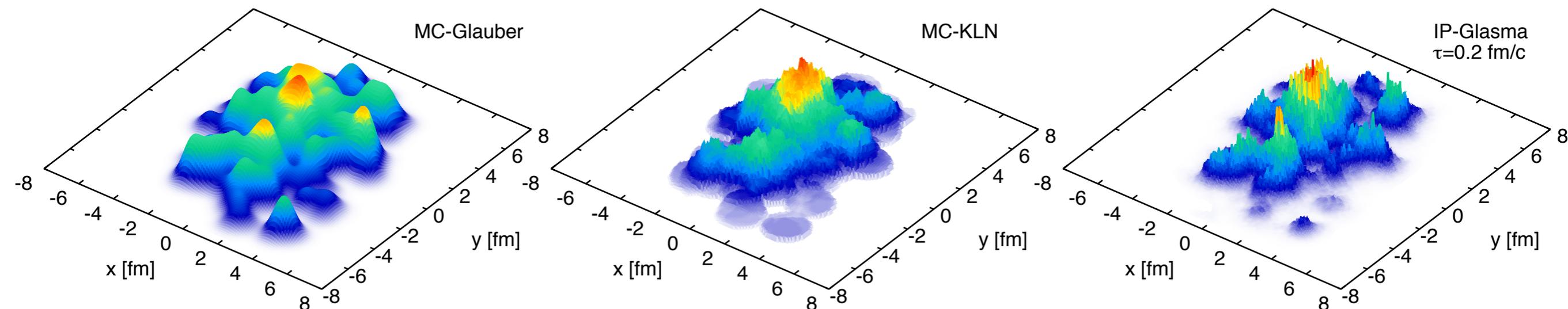
ALICE Coll., Phys. Lett. B719 (2013) 29-41; Phys. Rev. C 90, 054901

ATLAS Coll., Phys. Rev. Lett. 110, 182302 (2013), Phys. Lett. B 725 (2013) 60-78, Phys. Rev. C 90.044906 (2014)

CMS Coll., arXiv:1502.05382

# Heavy ions: Initial conditions

- Models need to provide input for fluid dynamic simulations: initial energy density, flow velocities, shear stress tensor
- Initial conditions fluctuate from event to event
- Main source of fluctuations: nucleon positions
- Different models give different *energy density distributions*



# Computing the initial state at high energies

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B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Gluon number increases with decreasing gluon momentum
- Gluon saturation at  $p_T \lesssim Q_s(x, \mathbf{b})$
- Strong fields with occupation  $\sim 1/\alpha_s$   
Classical description possible
- IP-Sat model parametrizes  $Q_s(x, \mathbf{b})$   
(simple way to include impact parameter dependence)  
KOWALSKI, TEANEY, PHYS.REV. D68 (2003) 114005
- Fit parameters to HERA diffractive data

# IP-Glasma initial conditions

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Sample nucleons from Woods-Saxon distribution
- Sample color charge density  $\rho^{A/B}(\mathbf{x}_T)$
- For nucleus A and B compute the path-ordered exponential over its longitudinal extend

$$V_{A/B}(\mathbf{x}_T) = \prod_{k=1}^{N_y} \exp \left( - ig \frac{\rho_k^{A/B}(\mathbf{x}_T)}{\nabla_T^2 + m^2} \right)$$

- $m$  is an infrared cutoff of order  $\Lambda_{\text{QCD}}$
- Wilson lines after the collision are then obtained from  $V_A$  and  $V_B$  via the Yang-Mills equations

# IP-Glasma initial conditions

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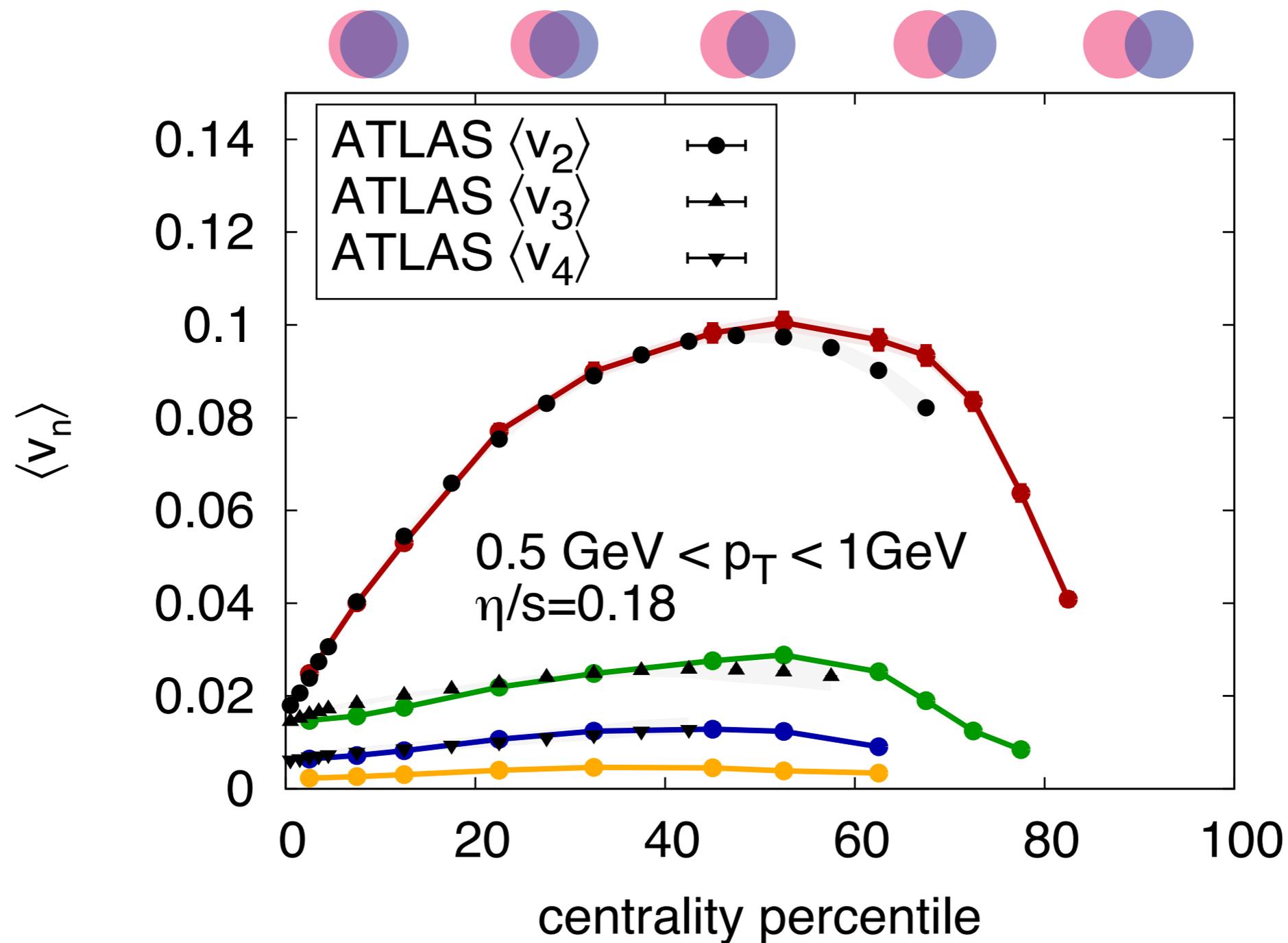
B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Yang-Mills equations determine:
  - Initial gluon fields from color charges  
KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237
  - Energy density after the collision
  - Early non-equilibrium time evolution
- Then match fields'  $T^{\mu\nu}$  to hydrodynamics by extracting  $\varepsilon$  and  $u^\mu$

# Results in Pb+Pb collisions: Average $v_n$

EXPERIMENTAL DATA: ATLAS COLLABORATION, JHEP 1311 (2013) 183

B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301



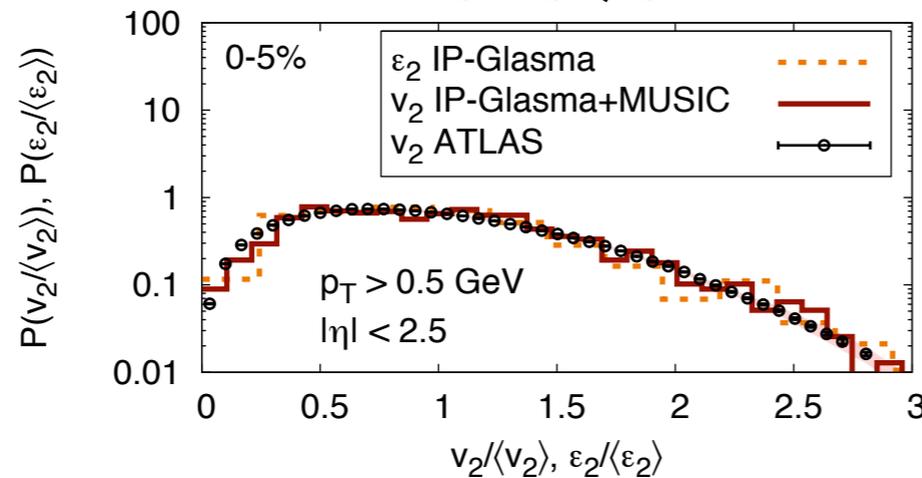
# Results in Pb+Pb collisions: Event-by-event $v_n$

ATLAS COLLABORATION, JHEP 1311 (2013) 183

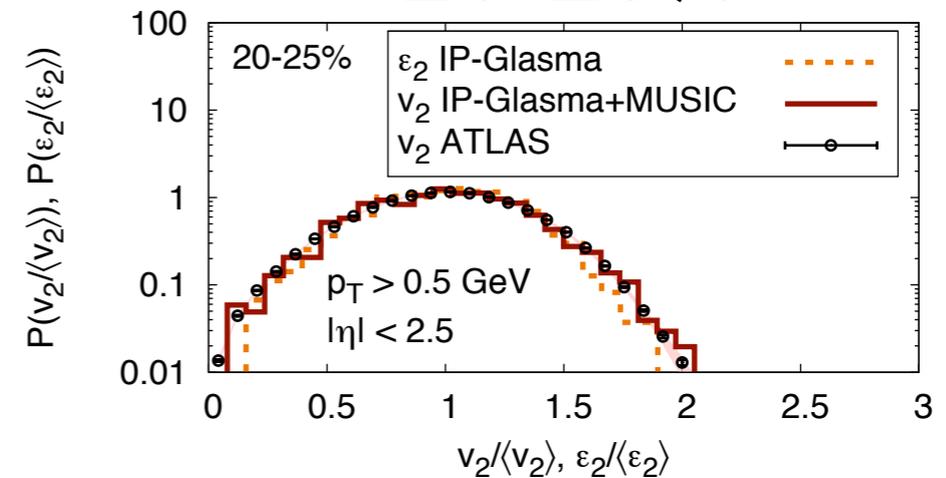
C. GALE, S. JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL110, 012302 (2013)

$v_2$

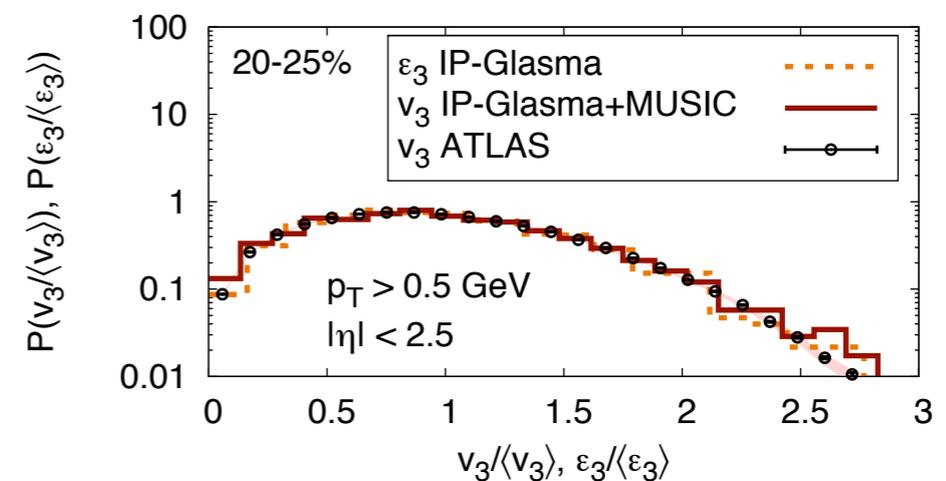
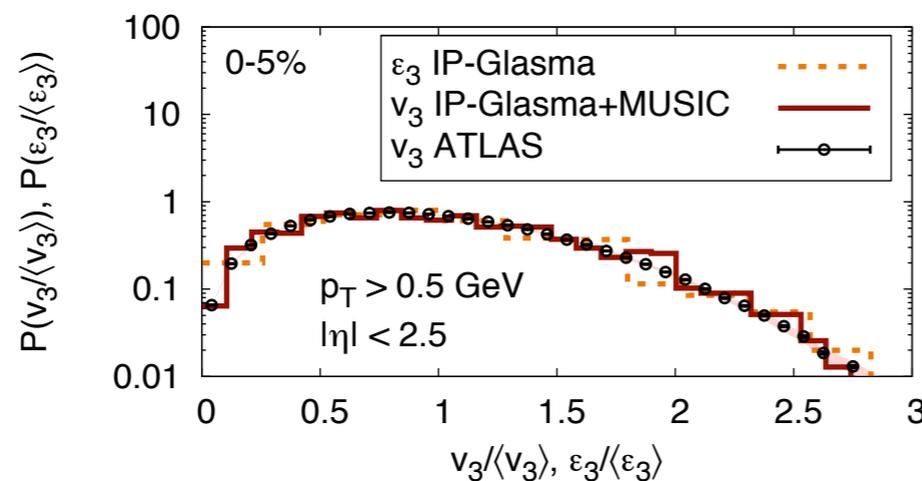
0-5%



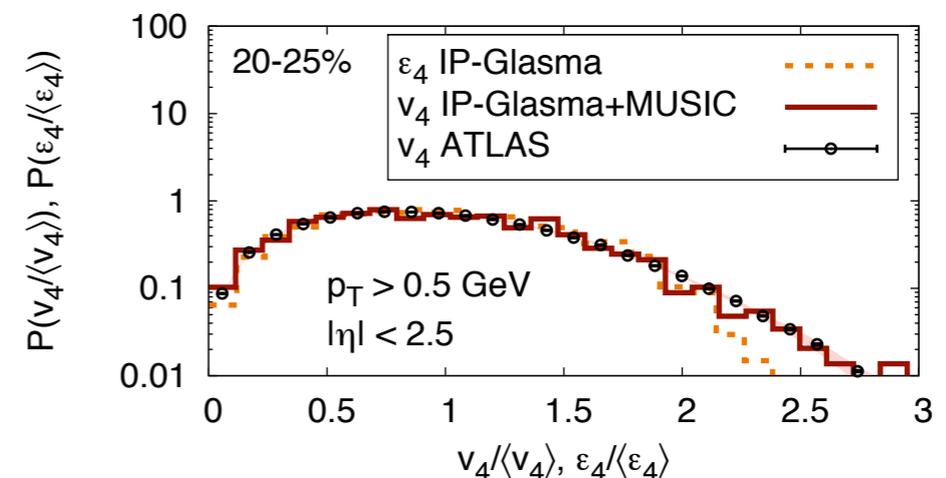
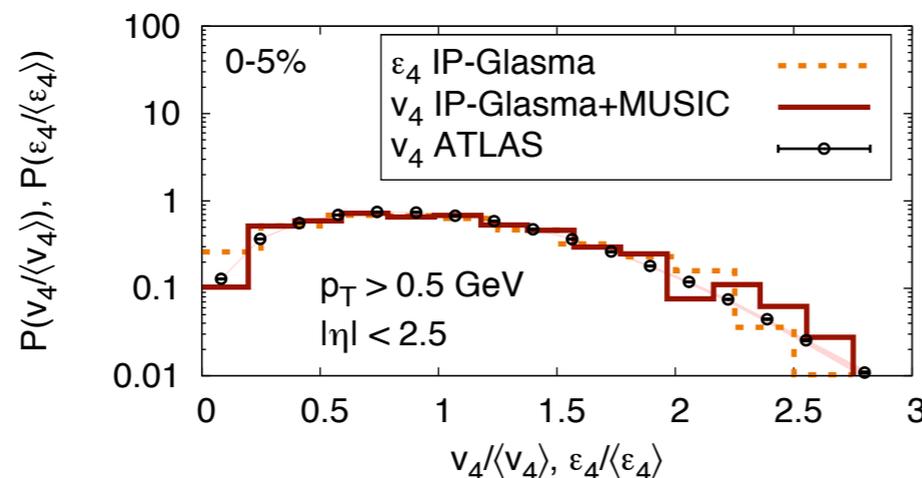
20-25%



$v_3$



$v_4$



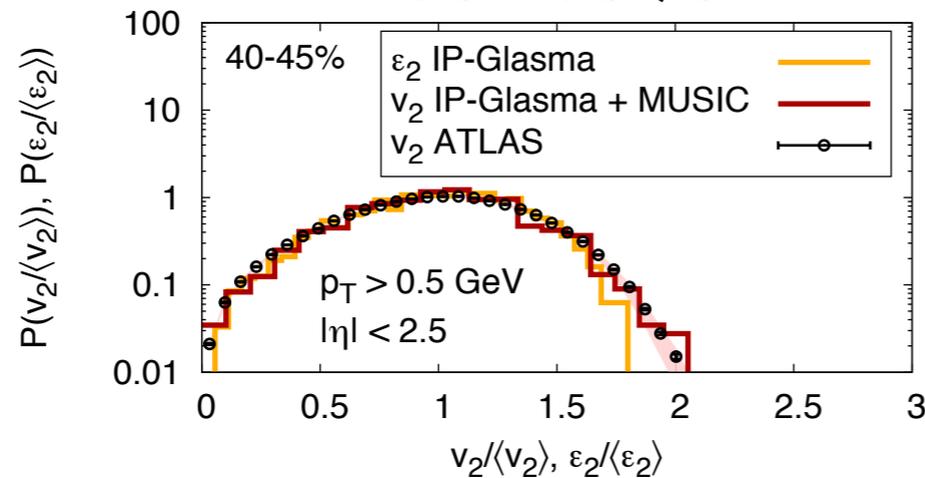
# Results in Pb+Pb collisions: Event-by-event $v_n$

ATLAS COLLABORATION, JHEP 1311 (2013) 183

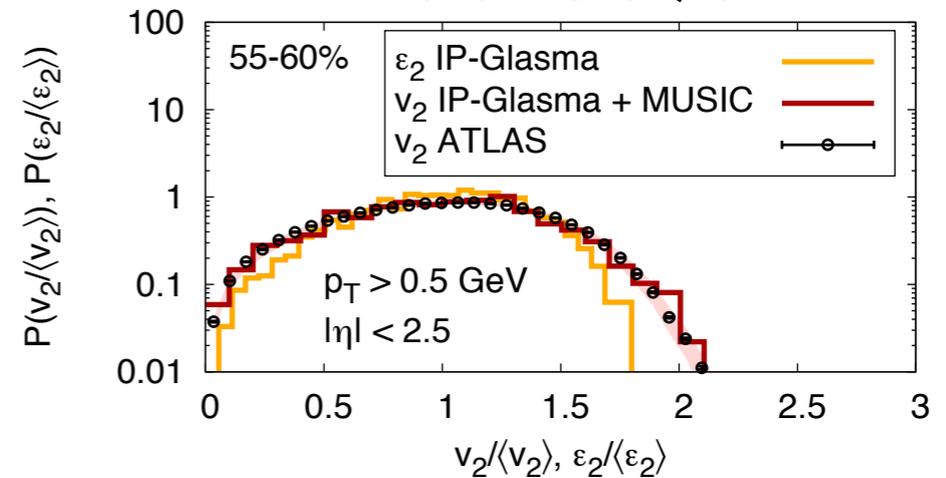
B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301

$v_2$

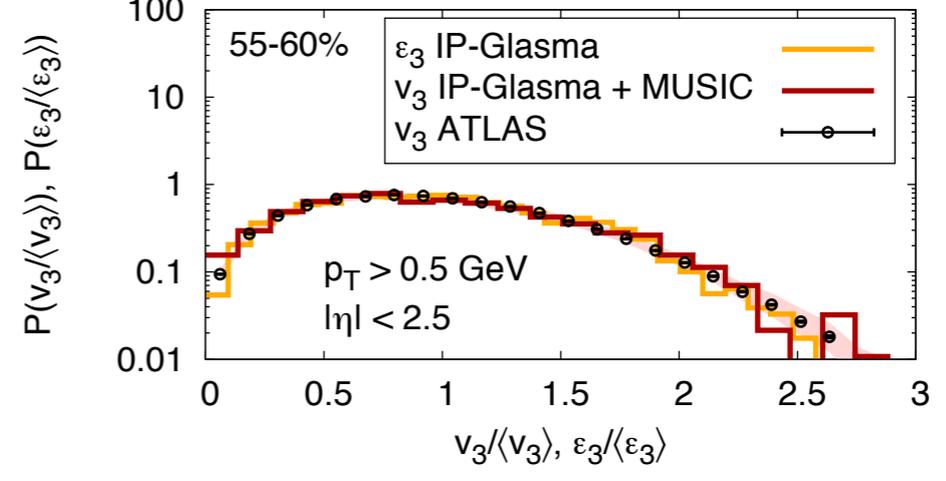
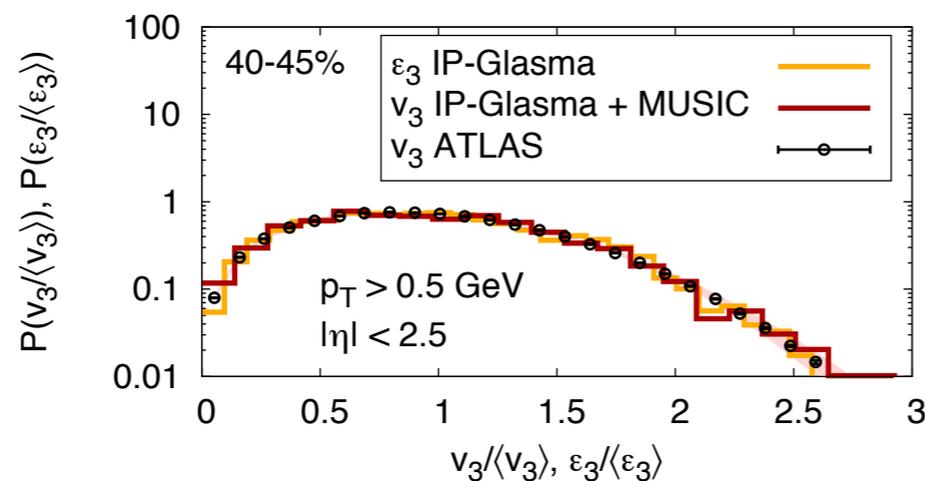
40-45%



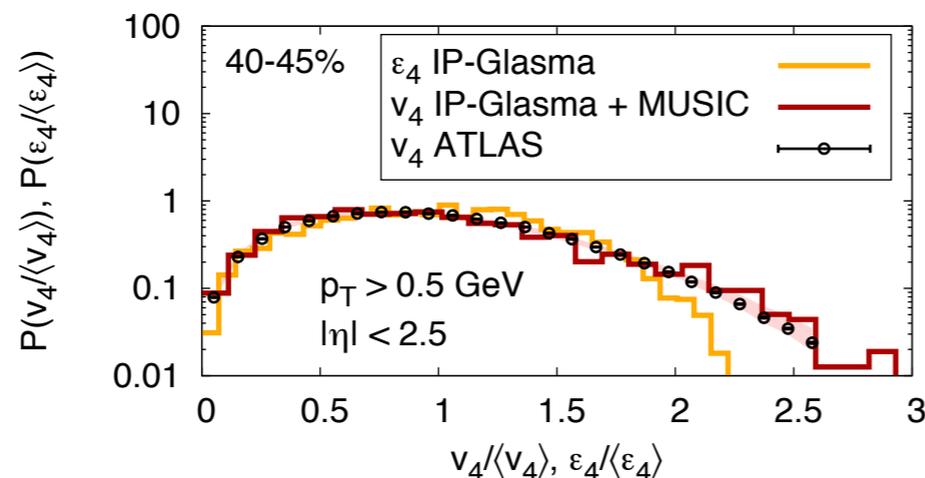
55-60%



$v_3$



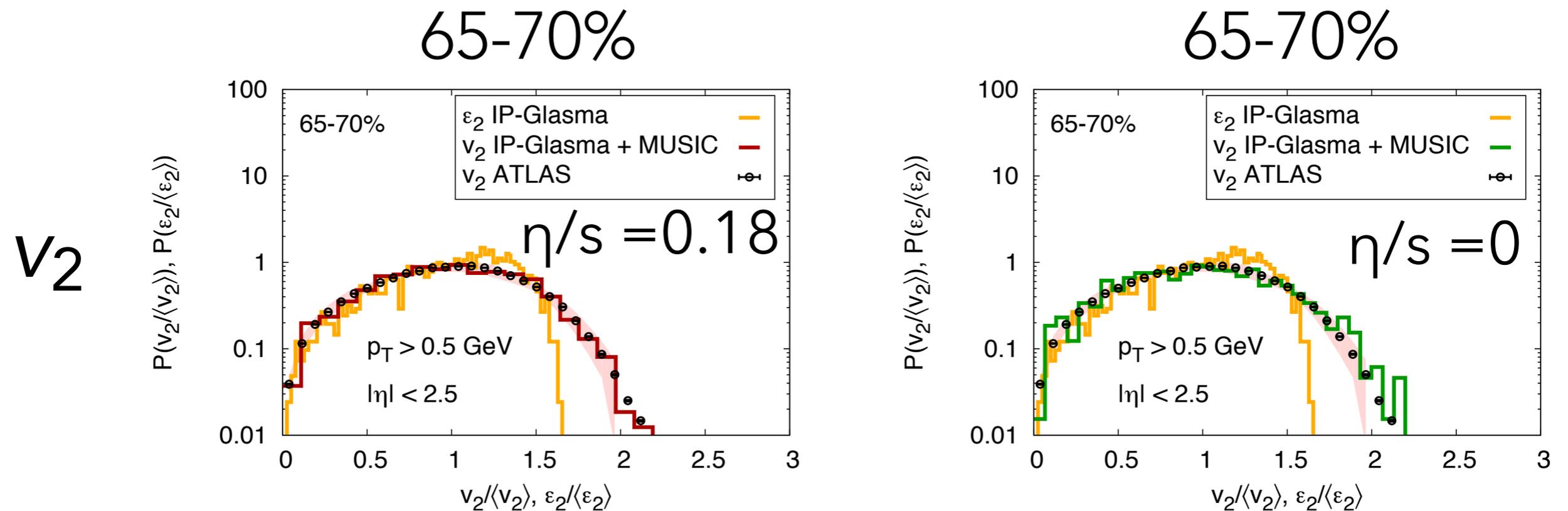
$v_4$



# Results in Pb+Pb collisions: Event-by-event $v_n$

ATLAS COLLABORATION, JHEP 1311 (2013) 183

B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301



Non-linearities in hydrodynamics are important  
Detailed transport properties are not

# So how do we do in small systems?

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- **System size:**

Systematics of initial size vs. HBT

- **$v_n$  in p+Pb:**

Energy deposition, effect of proton shape

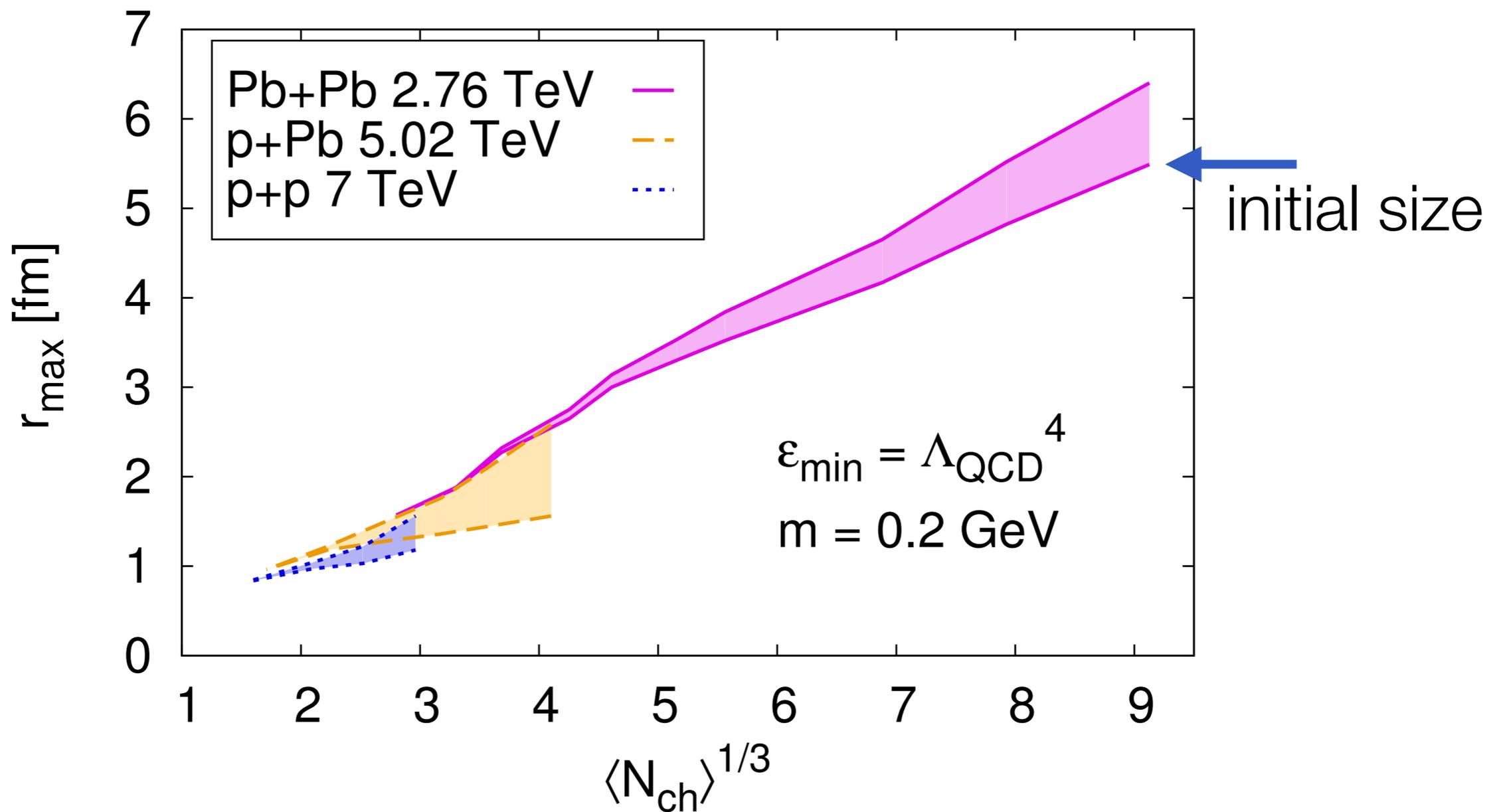
- **$v_n$  in d+Au and  $^3\text{He}+\text{Au}$ :**

predictions and data comparison

# System Size

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)

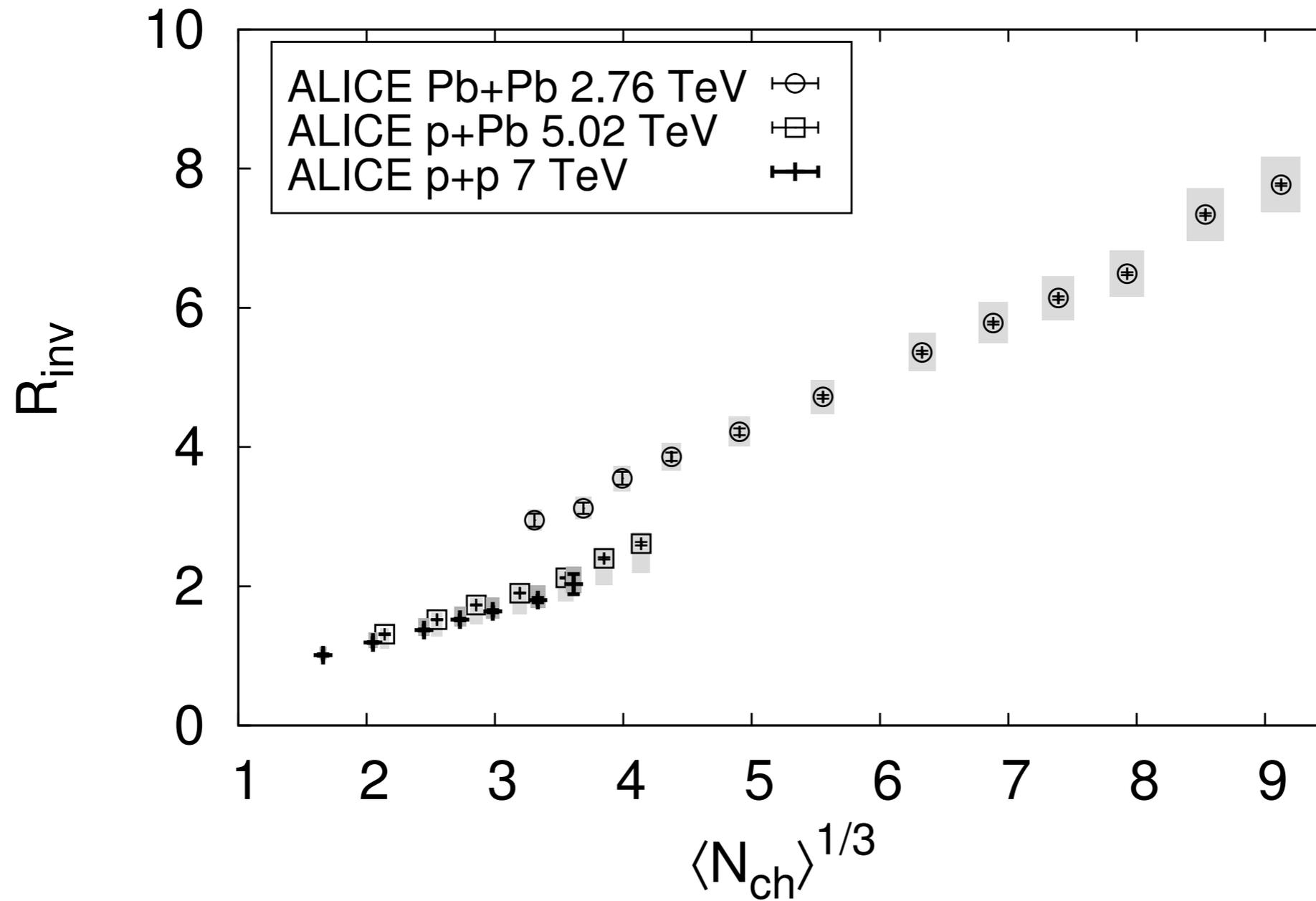
B. SCHENKE, R. VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301



Initial size in p+Pb closer to that in p+p than p+Pb

# System Size: Same trend seen in data

HBT DATA: ALICE COLLABORATION, PHYS.LETT. B739 (2014) 139-151

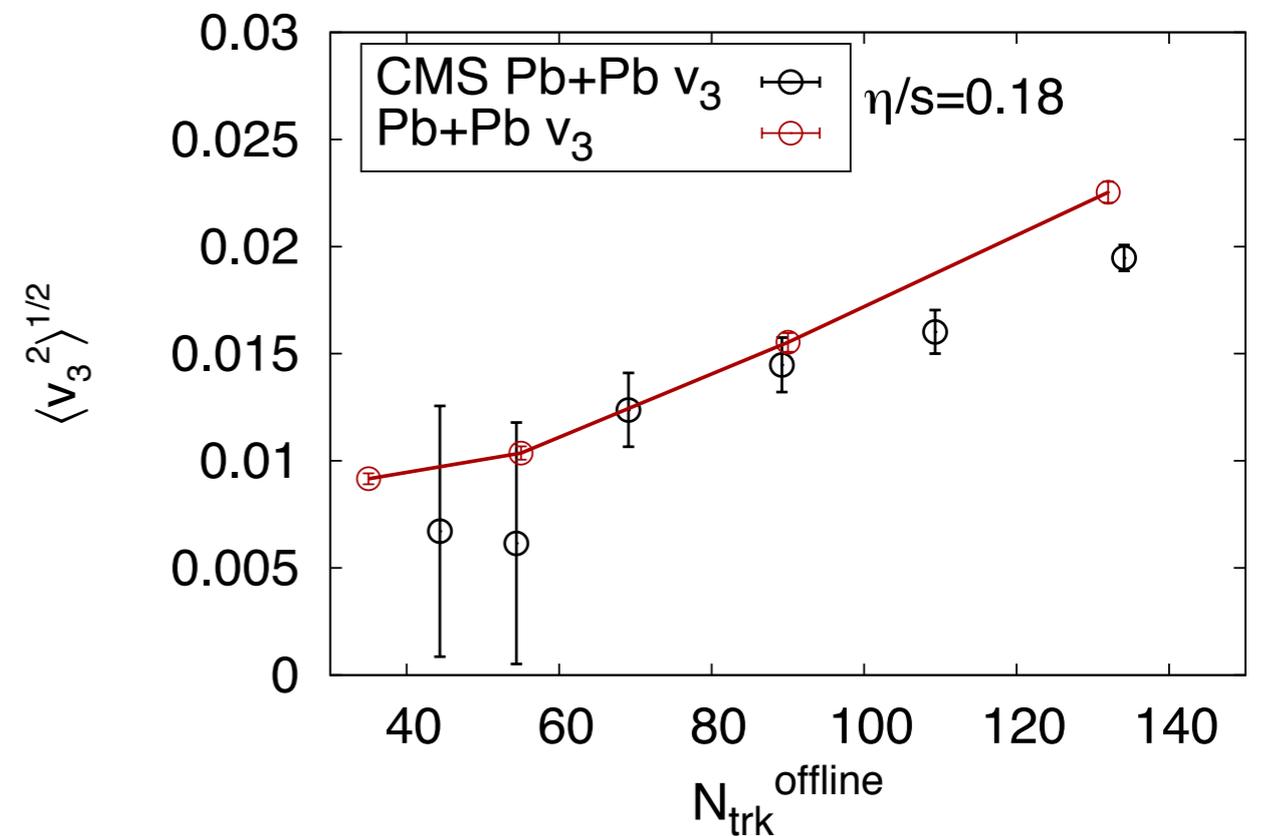
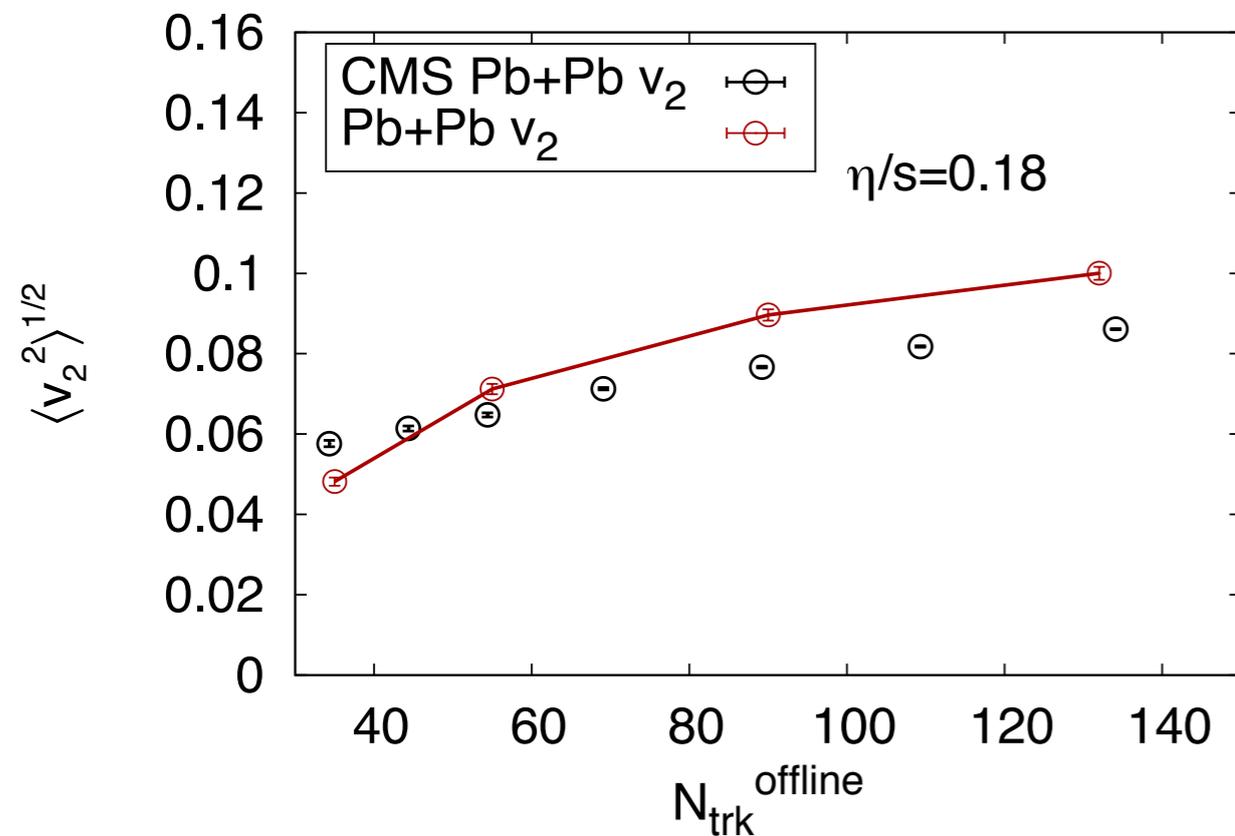


$R_{inv}$  in p+Pb closer to that in p+p than p+Pb

# Fourier Harmonics in p+Pb (and Pb+Pb)

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301



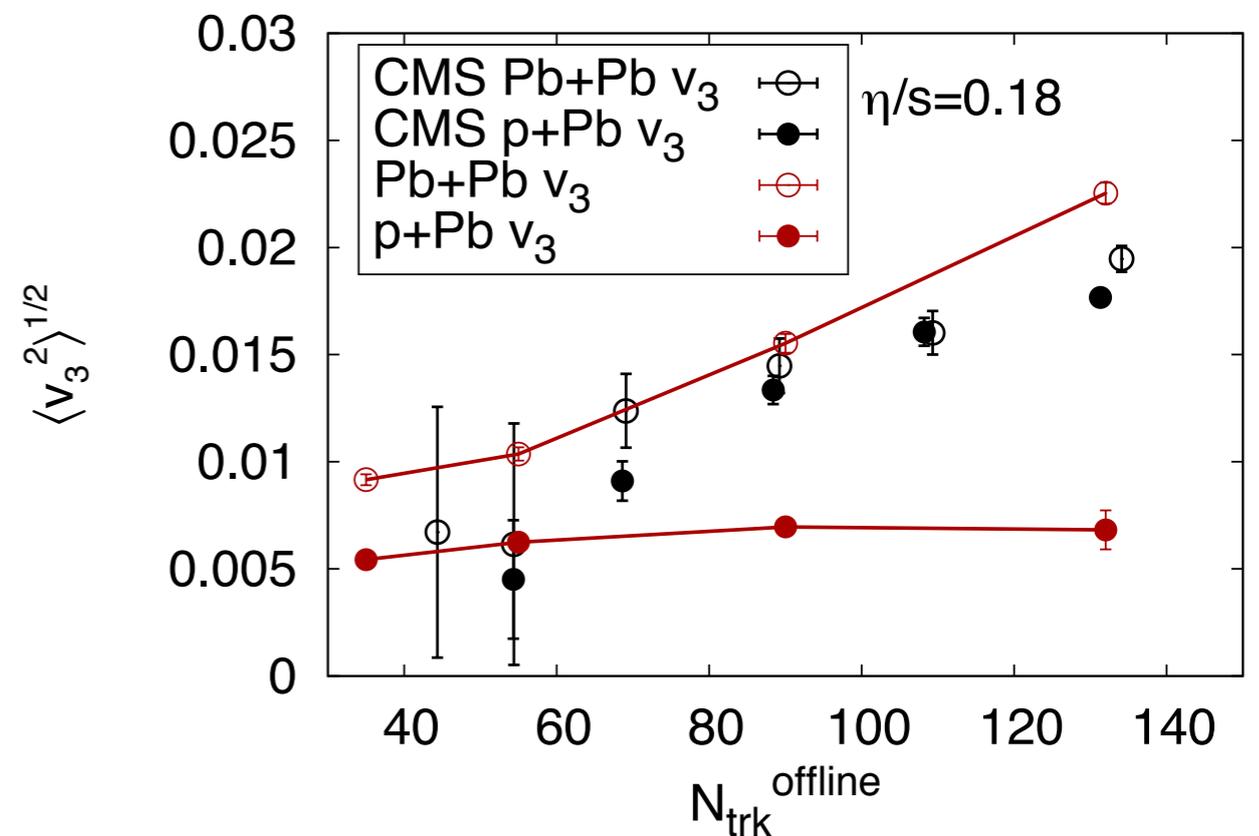
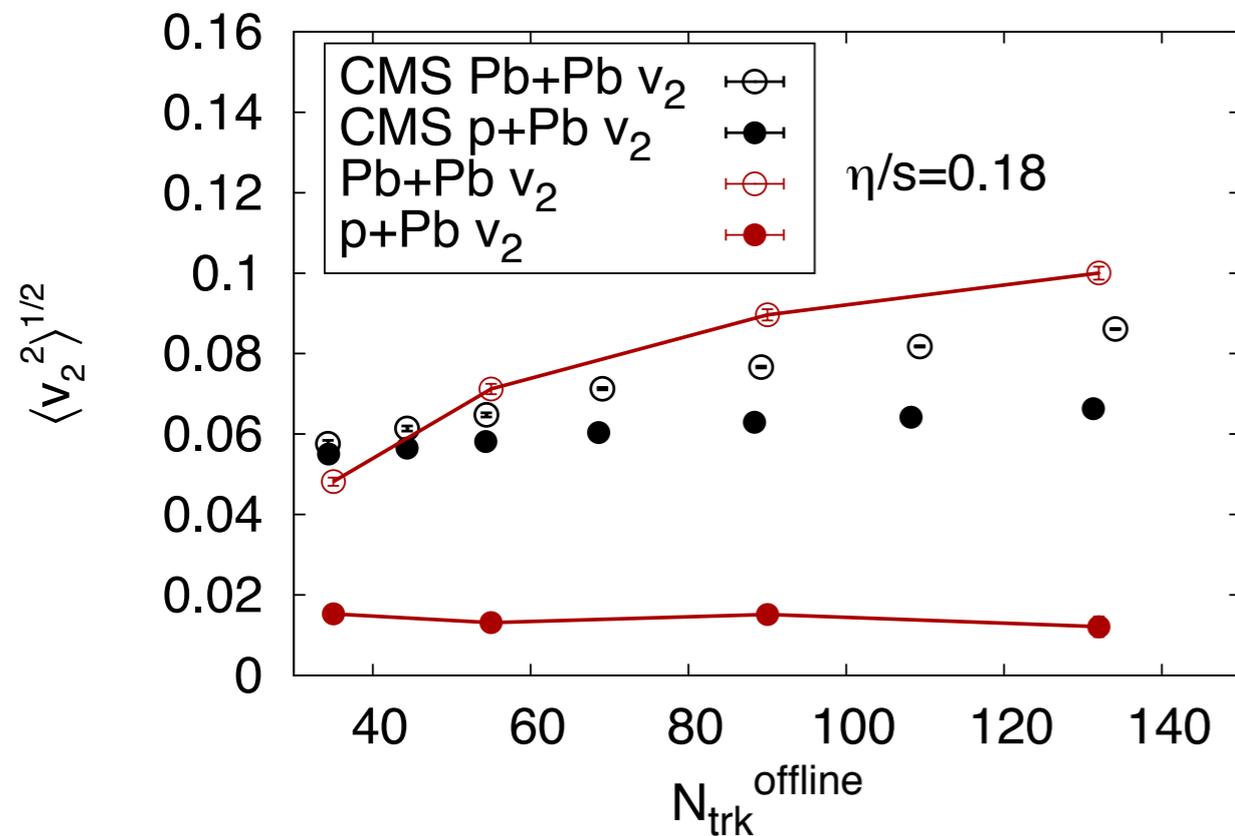
Open symbols: Pb+Pb

Red: IP-Glasma + MUSIC

# Fourier Harmonics in p+Pb (and Pb+Pb)

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301



Open symbols: Pb+Pb

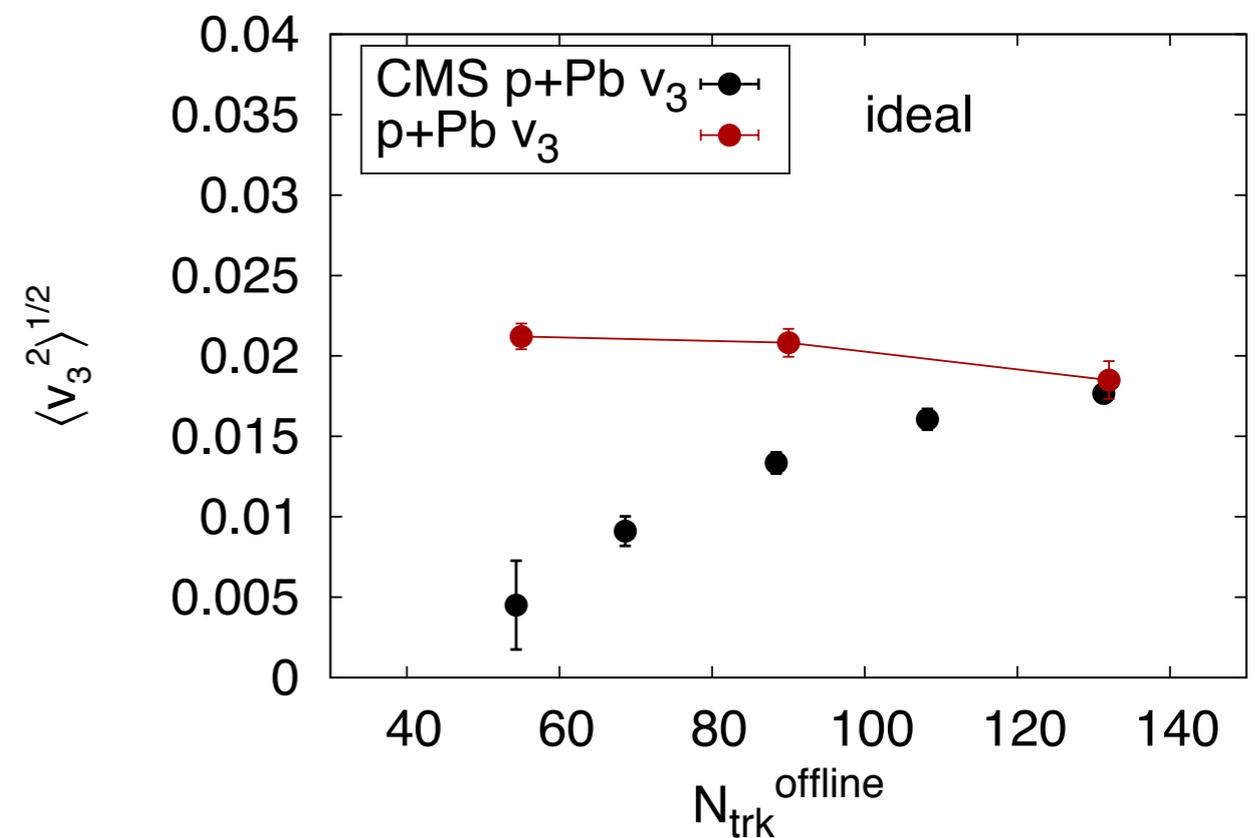
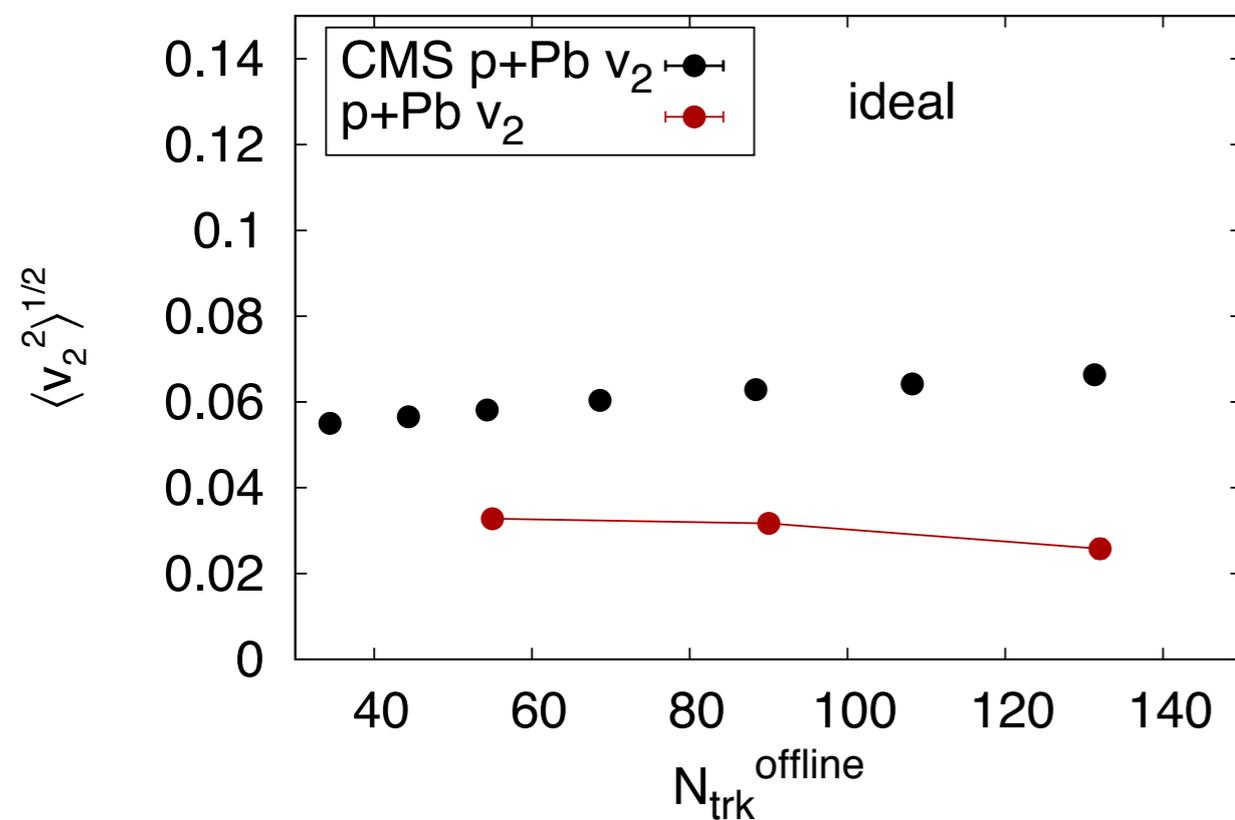
Filled symbols: p+Pb

Red: IP-Glasma + MUSIC

# Fourier Harmonics in p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301

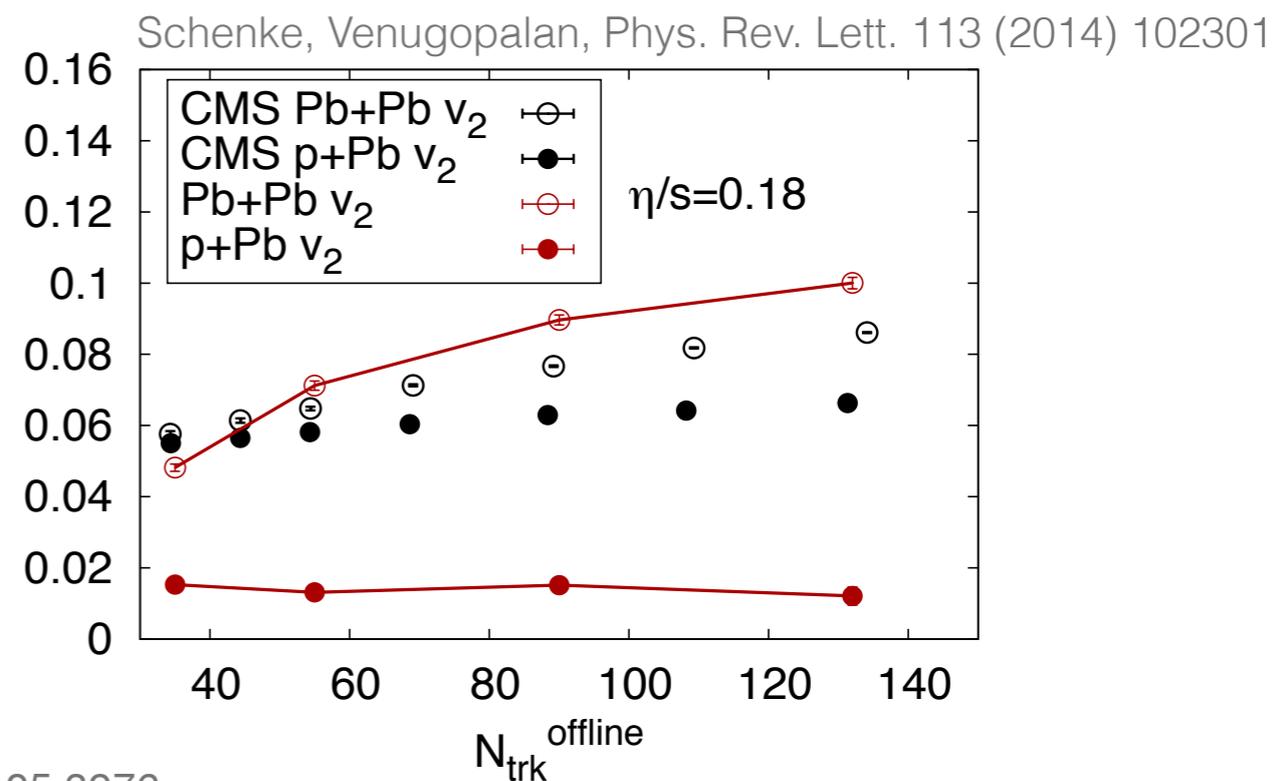
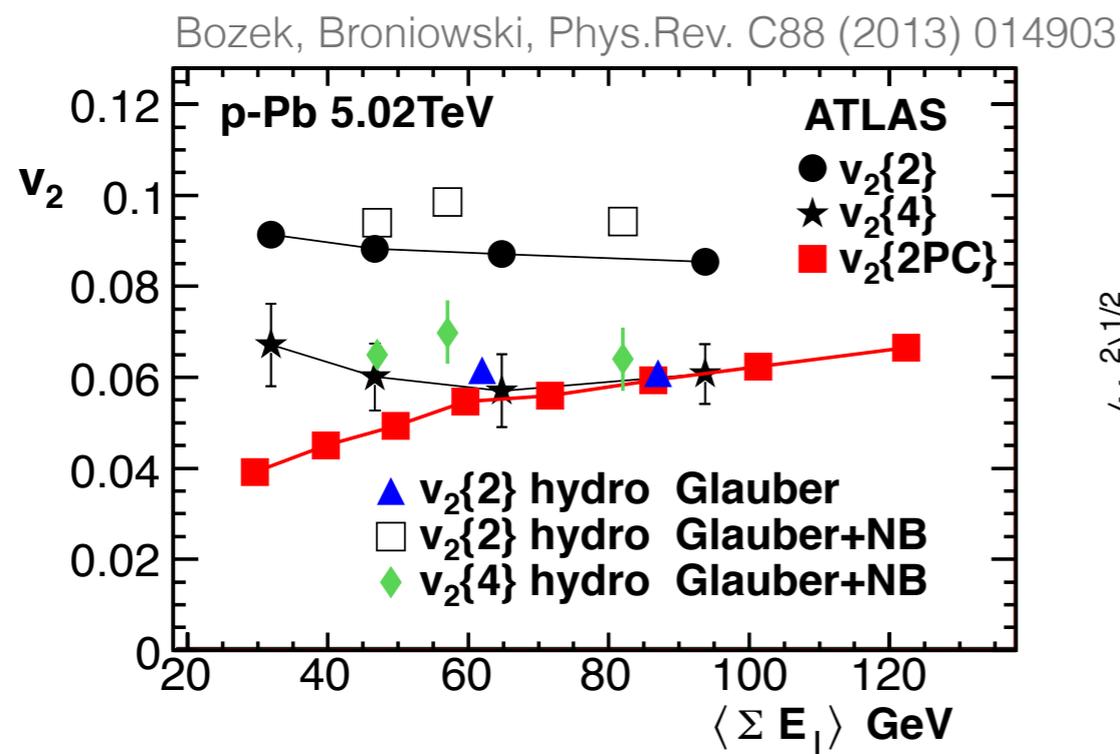


Filled symbols: p+Pb

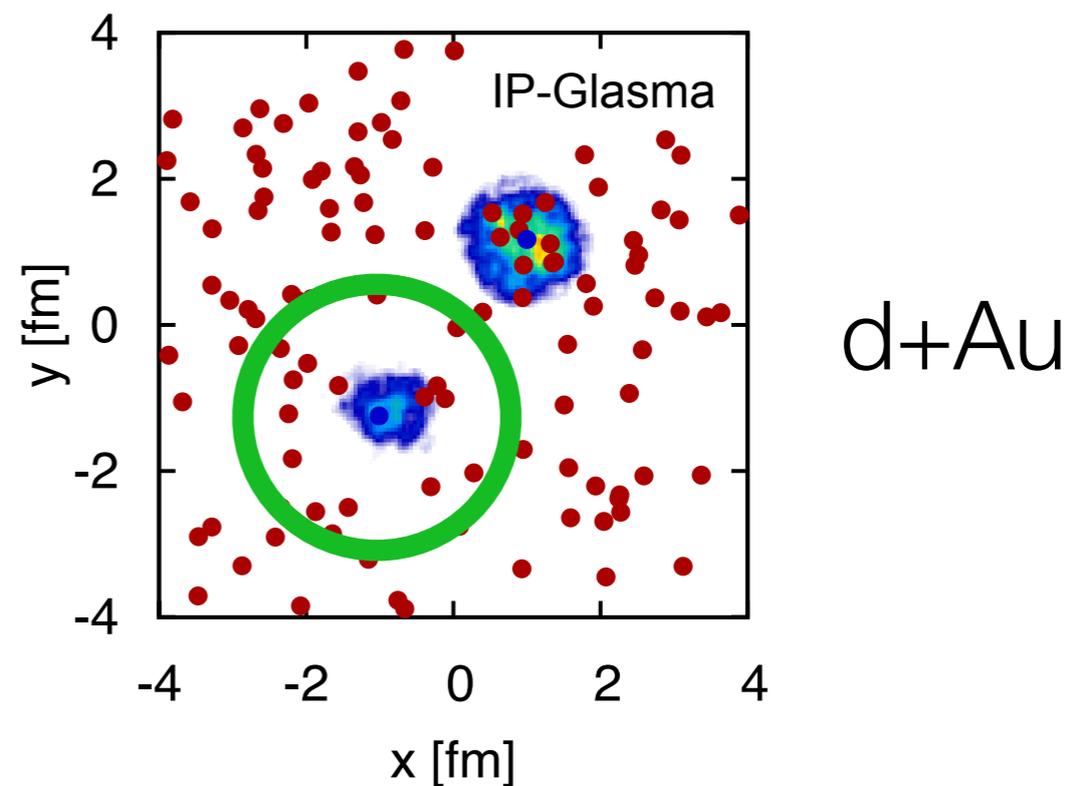
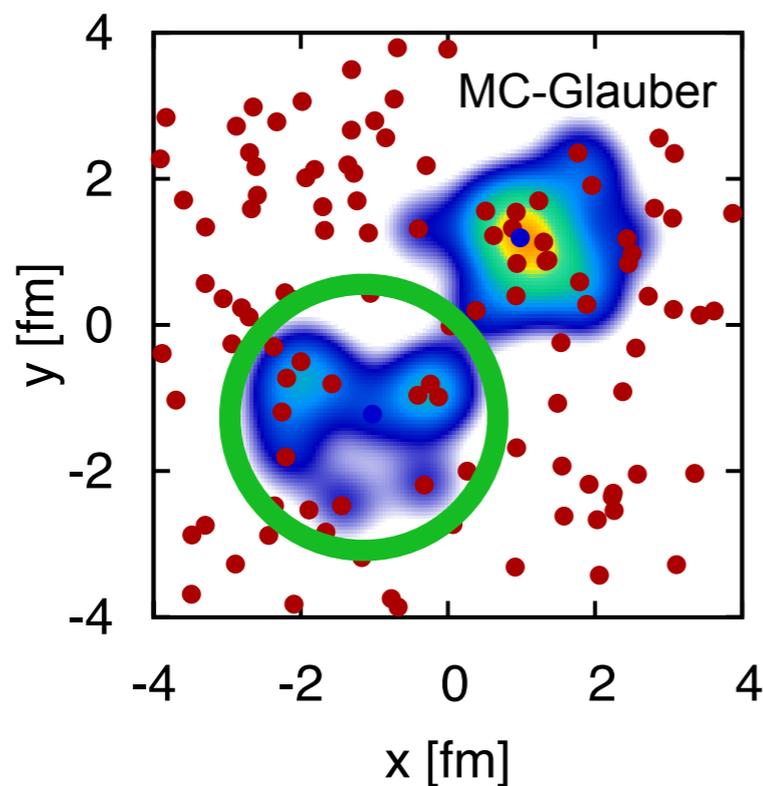
Red: IP-Glasma + MUSIC

IP-Glasma + hydro does not work at all for p+Pb collisions

# Difference to other hydro calculations: Initial state



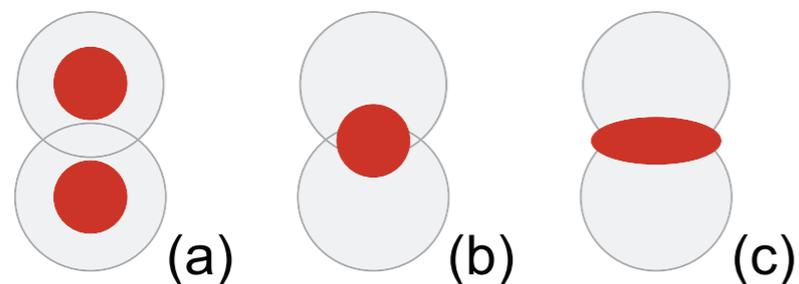
see also: Kozlov, Luzum, Denicol, Jeon, Gale, arXiv:1405.3976



# Issues in small systems (p+p, p+A)

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- MC-Glauber does not constrain energy density dist.



Where do we put the energy?

What shape does it have?

- IP-Glasma constrains energy density deposition

However, it does not describe  $v_n$  in p+Pb

- Proton substructure should matter

(if main effect is of collective origin or not)

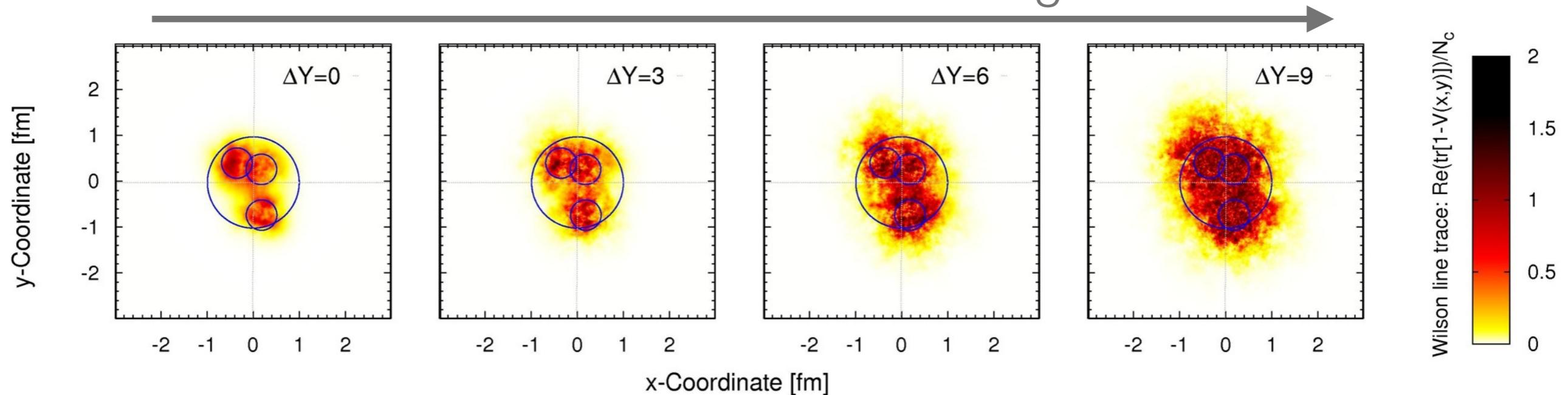
- Combine constituent quark model with JIMWLK evolution to get proton structure at small  $x$

# Are we sensitive to the shape of the proton?

S. SCHLICHTING, B. SCHENKE, PHYS. LETT. B739, 313-319 (2014)

- Three "Constituent quarks" at large  $x$
- JIMWLK evolution with infrared regulator to get gluon distribution at smaller  $x$

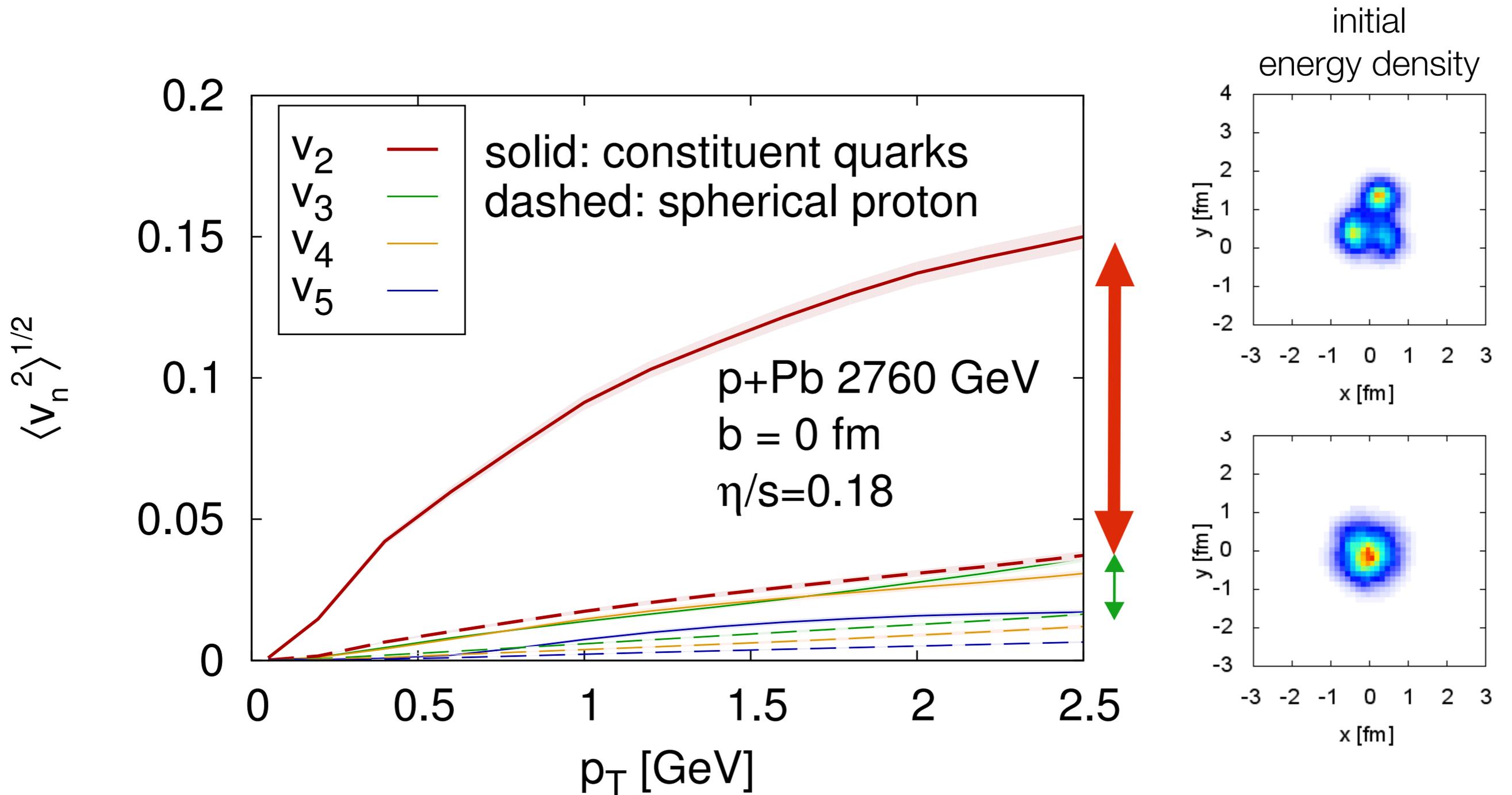
JIMWLK evolution: decreasing  $x$



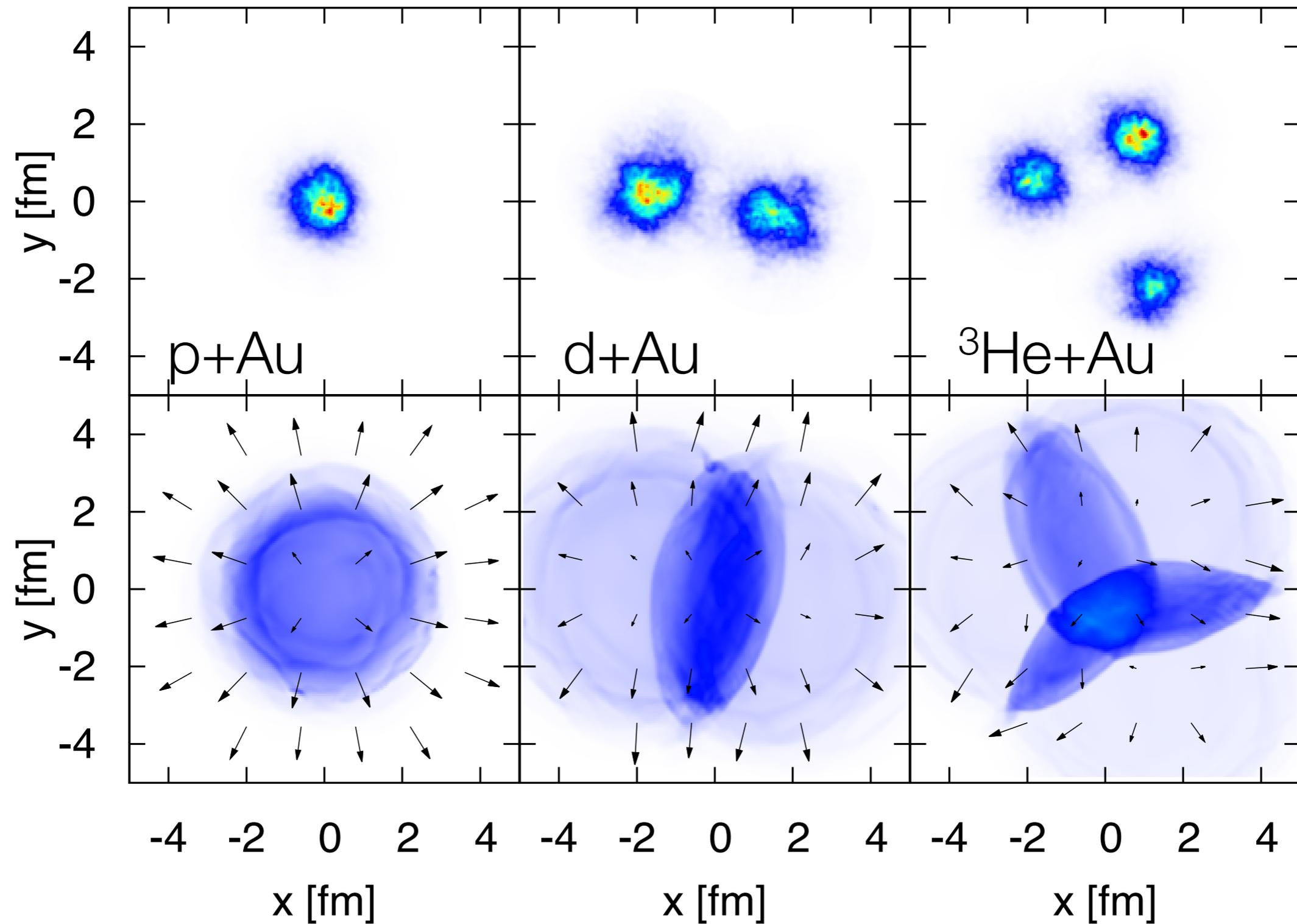
Hadron radius grows linearly with rapidity - "Gribov diffusion"  
Even at small  $x$  the proton is not a sphere of gluons

# Round vs. structured proton: IP-Glasma + Hydro

**It makes a huge difference for the flow harmonics!**



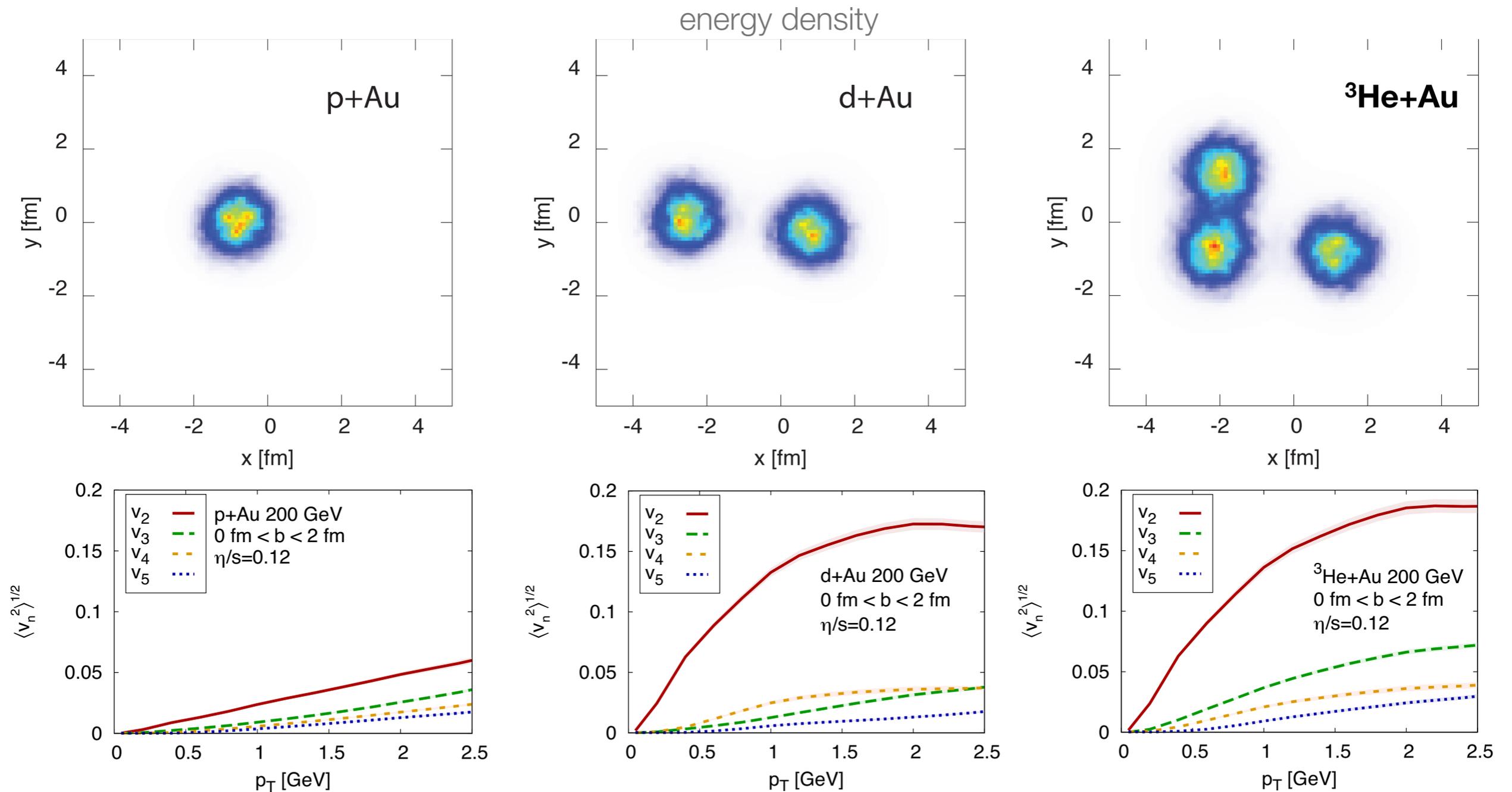
# Various small collision systems: IP-Glasma + MUSIC



# $^3\text{He}+\text{Au}$ results from IP-Glasma + MUSIC

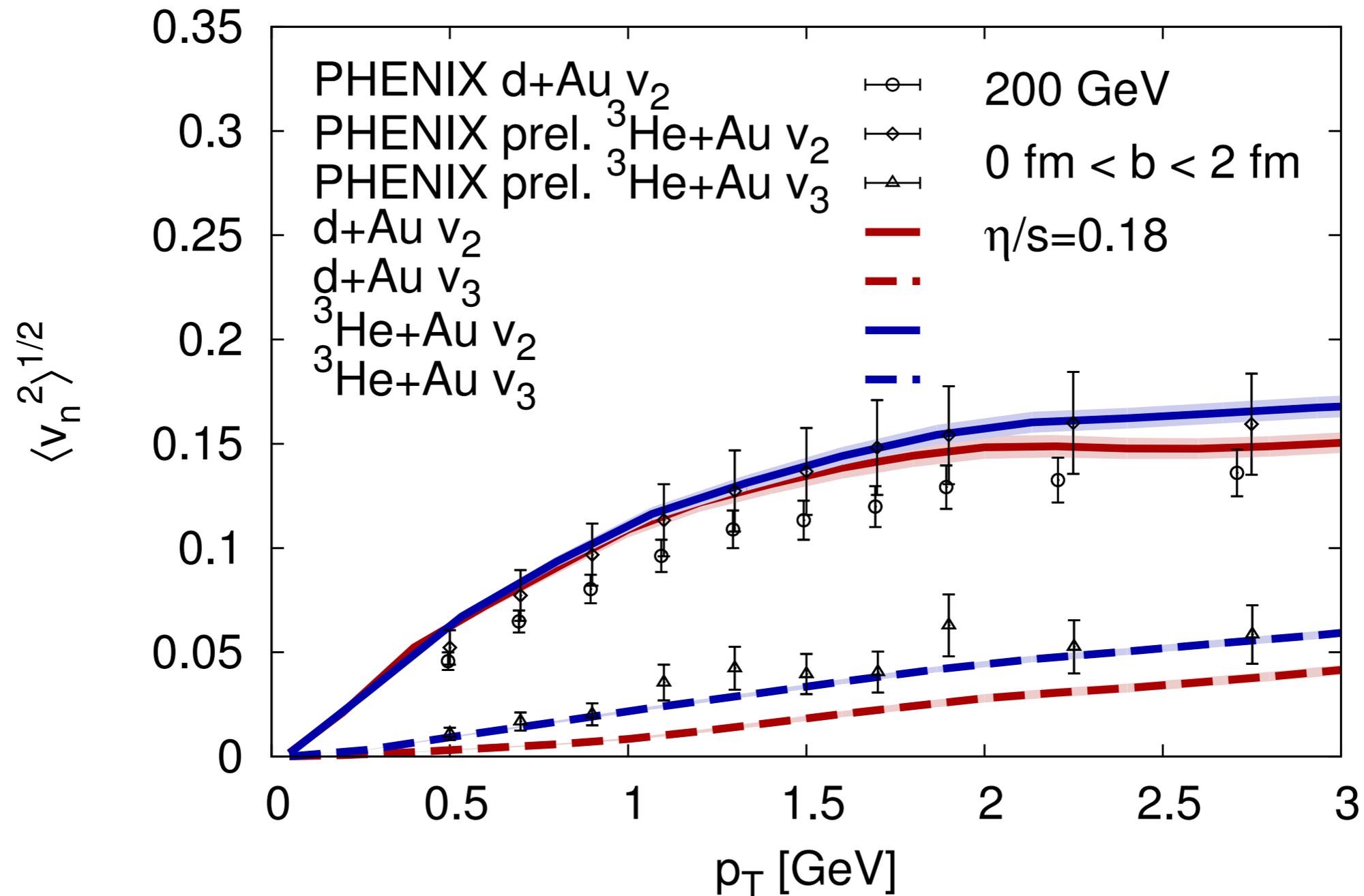
B. SCHENKE, R. VENUGOPALAN, NUCL.PHYS. A931 (2014) 1039-1044

Predictions for  $\eta/s = 0.12$ :



# $^3\text{He}+\text{Au}$ results from IP-Glasma + MUSIC

Adjust parameter:  $\eta/s = 0.18$  - compare d+Au and  $^3\text{He}+\text{Au}$



Note: No realistic centrality selection

# Is viscous fluid dynamics valid in small systems?

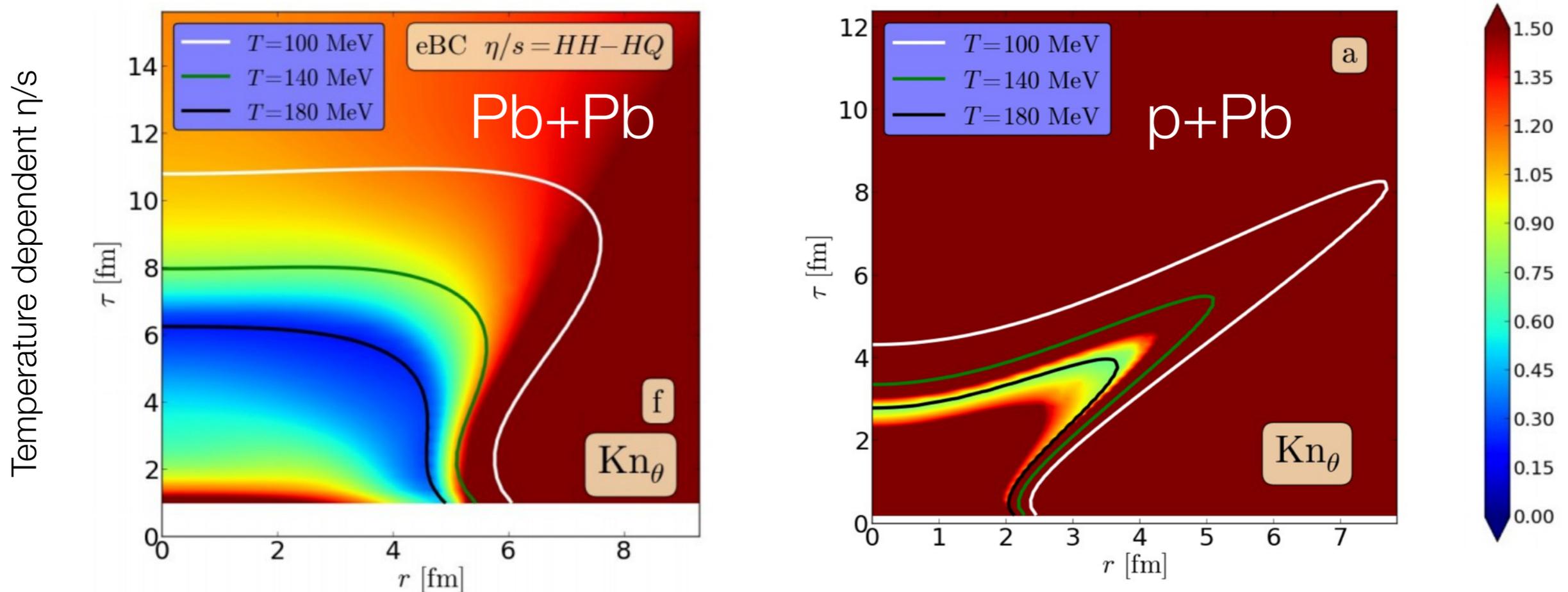
H. Niemi, G.S. Denicol, e-Print: arXiv:1404.7327

- Use the Knudsen number as a measure

$$Kn_{\theta} = l_{\text{micro}} / L_{\text{macro}}^{\theta} = \tau_{\pi} \theta \quad (\text{this is one specific choice})$$

where  $\tau_{\pi}$  is the shear relaxation time and  $\theta = \partial_{\mu} u^{\mu}$

- Small Knudsen number means fluid dynamics is valid



# Is viscous fluid dynamics valid in small systems?

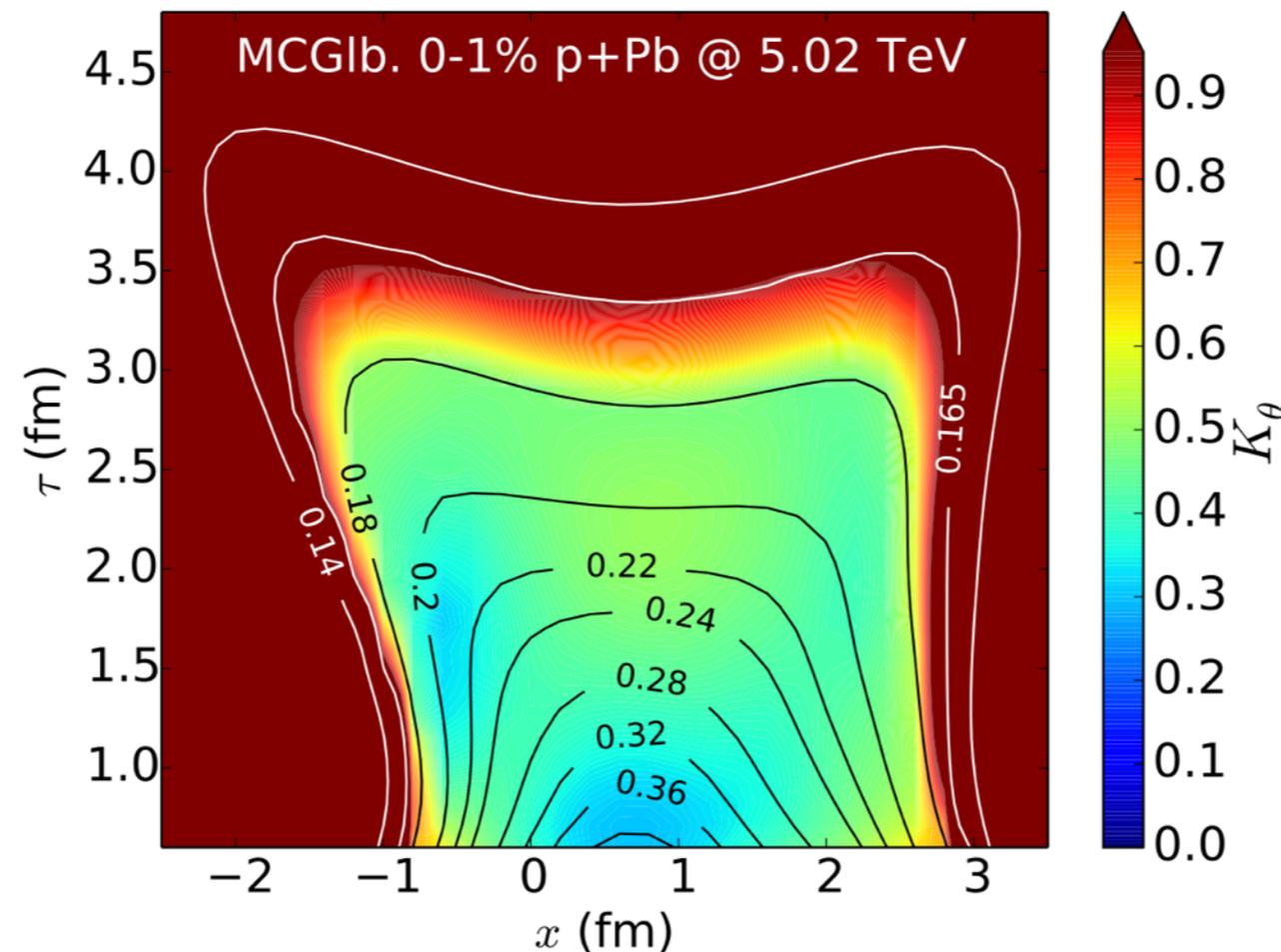
C. Shen, J. -F. Paquet, G.S. Denicol, S. Jeon, C. Gale, arXiv:1504.07989

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where  $\tau_\pi$  is the shear relaxation time and  $\theta = \partial_\mu u^\mu$

- Ultra-central p+Pb collisions do not look so bad if freezing out at 165 MeV:



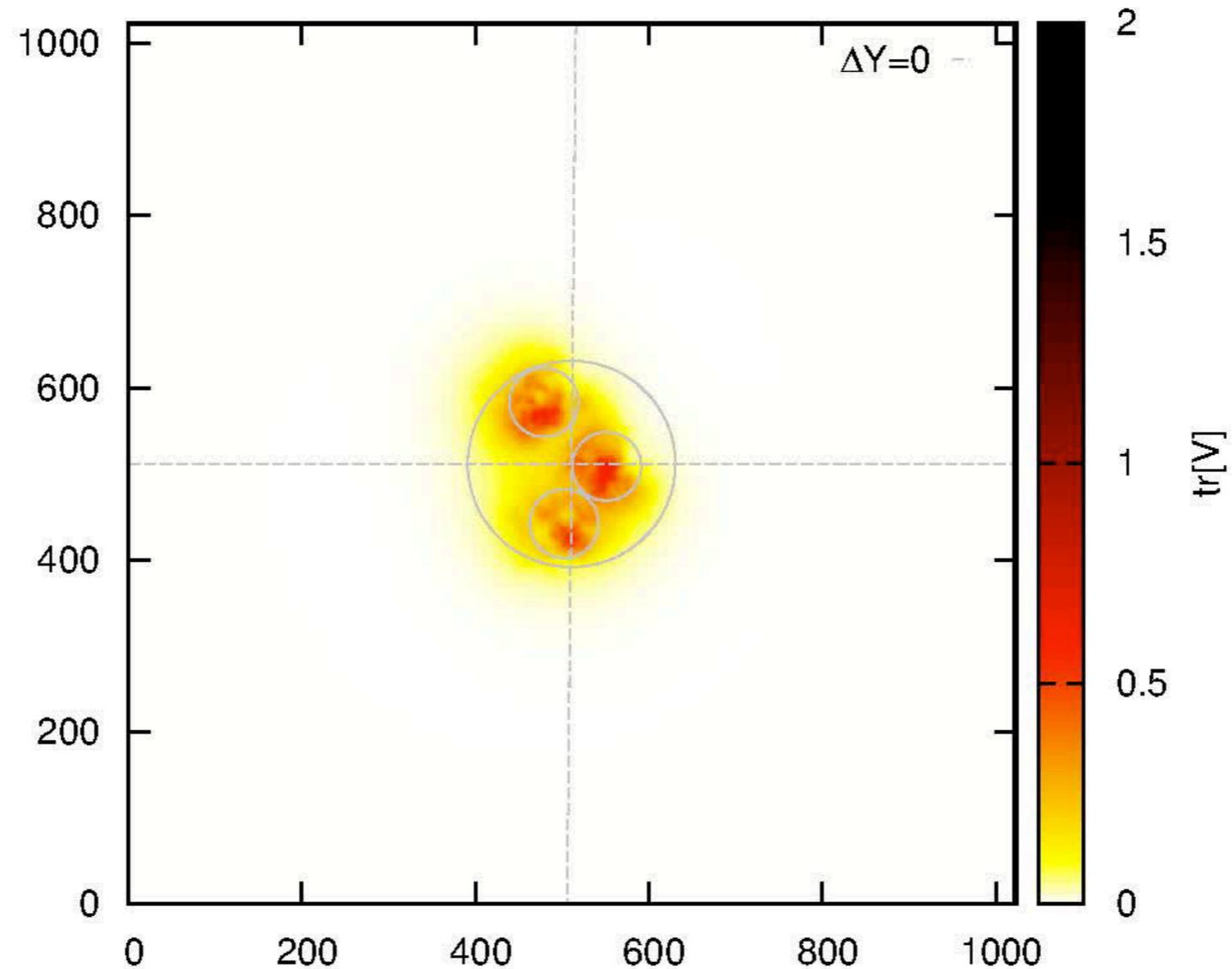
# Conclusions

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- Relativistic fluid dynamics has been very successful in describing bulk properties of heavy ion collisions
- In p+A collisions hydro results are highly sensitive to the substructure of the proton
- In small systems there are also contributions to anisotropic particle production from the initial state (K. Dusling's talk)  
However, they may not survive the final state interactions
- If so, the final state interactions fully account for the  $v_n$ 's and measurements can provide information on the substructure of the proton
- We always need to keep an eye on the validity of hydrodynamics and the potential errors we make by applying it

# JIMWLK evolution of a “lumpy proton”

S. SCHLICHTING, B. SCHENKE, PHYS. LETT. B739, 313-319 (2014)



FIXED COUPLING JIMWLK EVOLUTION  
OF TRACE OF THE WILSON LINE